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ONWI-352
UCRL-53142

ORIGINAL

Uncertainties and Sensitivities in the Performance of Geologic Nuclear Waste Isolation Systems

Volume I
Summary

COMPLETED
37

Technical Report

April, 1981

W. G. Sutcliffe
K. G. Feller
N. K. Madsen
G. D. Pollak

Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

ONWI
Office of Nuclear Waste Isolation

BATTELLE Project Management Division

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BIBLIOGRAPHIC DATA

Sutcliffe, W. D., K. G. Feller, N. K. Madsen, and G. D. Pollak, 1981. *Uncertainties and Sensitivities in the Performance of Geologic Nuclear Waste Isolation Systems,* Volume I, *Summary,* ONWI-352 (UCRL-53142), Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

ONWI-352
UCRL-53142
Distribution Category UC-70

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This report was prepared by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48 with the U.S. Department of Energy. This contract was administered by the Battelle Office of Nuclear Waste Isolation.

I

PREFACE

This report is being issued as two volumes. Volume II is the complete report. Volume I, Summary, is a reproduction of some parts of Volume II, and contains no additional information.

Those parts of Volume II which are reproduced in Volume I, Summary are:

- Section 1, Introduction and Summary
- Figures referenced in Section 1 (Appendix A in Volume I)
- Table of Contents of Volume II (Appendix B in Volume I).

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SUMMARY: UNCERTAINTIES AND SENSITIVITIES IN THE PERFORMANCE OF GEOLOGIC NUCLEAR WASTE ISOLATION SYSTEMS

ABSTRACT

This report presents an analysis of the long-term safety of geologic nuclear waste isolation systems. The study focuses on the effect of uncertainty about engineered and natural systems. We identify the subsystems and parameters that dominate the system performance under various conditions. We also consider the potential differences between waste forms, host media, and site characteristics, and how these differences affect the system's performance.

The scope of this study is limited to probabilistic analysis of nuclear waste migration via groundwater flow in assumed pathways. The primary measure of performance is the peak rate of activity release (Ci/yr) at the end point of a pathway.

As well as demonstrating methods for uncertainty analysis, we present specific results and conclusions. Deterministic and probabilistic parametric analyses cover a range of parameter values large enough to encompass significantly different waste forms, packages, and sites (in various media). The results are useful for the assessment of geologic waste isolation systems in general. We also analyze specific hypothetical systems using generic data.

The following are some general observations:

- A global, parametric analysis is more informative than a local sensitivity analysis.
- Individual contributions of "multiple barriers" (subsystems) are sometimes insignificant.
- Some uncertainties have little effect on system performance.

1. INTRODUCTION AND SUMMARY

This report analyzes the sensitivities and uncertainties in the long-term safety of geologic nuclear waste isolation systems. This section briefly describes the purpose and scope of the study, the technical approach and models, some results and conclusions, and recommendations for additional work.

1.1 BACKGROUND AND PURPOSE

This study was conducted for the Office of Nuclear Waste Isolation (ONWI) to provide information useful in the development and assessment of technology to isolate nuclear waste. Often the most complicating factor in making decisions in this area is the uncertainty about the isolation system and its predicted performance.

These uncertainties arise because of:

- New technology
- Geologic variability
- Required long-term safety

The importance of individual uncertainties is difficult to assess. Our overall goal is to demonstrate a method for quantifying and evaluating the importance of various uncertainties. Our particular objective is to identify which uncertainties about individual subsystems are important in terms of complete system. We identify the conditions under which various subsystems and parameters dominate. We also consider the potential differences between waste forms, host media, and site characteristics, and how these differences affect assessed system performance, particularly when uncertainties are considered.

1.2 STUDY SCOPE

The scope of this study is limited to the post-closure, radiologic safety of mined repositories for nuclear waste. Only leakage via groundwater was considered. The analysis assumed scenarios where hydrologic pathways exist. The study did not address specific mechanisms for creating these pathways or the probabilities that such pathways exist. Thus, the study focused on probabilistic analysis of the consequences.

Assuming significant pathways exist, we allowed probability distributions to represent uncertainties about the hydrologic and chemical properties that control vast transport along these paths. We also used probability distributions to represent uncertainty about the life of waste packages and the rate of waste leaching from degraded packages.

An analysis covered a range of parameter values large enough to encompass significantly different sites in various media, waste forms, and packages.

These results can be applied generally to isolation systems that we represented by a point source embedded in a sequence of serially connected pathways.

Specific hypothetical systems were analyzed using generic data to construct cases for analysis. Major emphasis was placed on spent-fuel repositories, in bedded salt. A less extensive analysis was also conducted to investigate the differences between bedded salt and basalt media, and to compare the effects of spent fuel (SF) and high-level waste (HLW). High-level waste was assumed to be in a glass or SYNROC waste form.

1.3 TECHNICAL APPROACH

Waste isolation systems were represented by simple models applied in parametric analyses over very broad ranges of values to specific, hypothetical systems. The study included both deterministic and probabilistic analyses.

This approach consisted of:

- Characterization of the system
- Data acquisition
- Performance analysis
- Interpretation of results

The characterization, as discussed in Section 2, consists of assuming performance measures, constructing appropriate models (identifying parameters), and combining them to obtain an algorithm for calculating the performance measures.

The need to encompass the complete system and to evaluate uncertainty dictates the detail in the models. Subsystem models are simple algebraic models with a small number of parameters. Transport was computed using analytic solutions of one-dimensional differential equations. More complex mathematical functions are represented by tables. This approach allows the large number of calculations necessary to accomplish the sensitivity and uncertainty analyses.

The data acquisition effort, discussed in Section 4, consisted of obtaining and interpreting raw data, transforming the data into the necessary input, and finally quantifying the uncertainty in the data. The data were based on a literature survey and questioning of experts. For the most part we chose ranges of numbers that would be representative of a repository in salt.

Uncertainties were quantified by associating the 1st and 99th percentiles of log-normal distributions with the limits chosen. We used log-normal distributions because the range of data usually covered several orders of magnitude.

The performance analyses compute sensitivity, uncertainty, and sensitivity of uncertainty. Both deterministic and probabilistic calculations were performed. The deterministic results follow from a direct application of the models to be discussed. The probabilistic or uncertainty calculations used discrete elements to represent probability distributions.

Deterministic analyses assessed performance sensitivity to model parameters. Local sensitivity analysis (achieved by small variations in parameters) proved to be potentially misleading. The large parameter ranges (encompassed by uncertainty in parameter values and different systems) required a more global analysis. The primary method of deterministic sensitivity analysis was a parametric study with a few high-level parameters. The results are presented as contour plots in Section 5. Performance sensitivity to each model parameter depends on the values of the other parameters. Each has domains of high and low sensitivity, depending on the values of all the model parameters. Thus, the uncertainty of a parameter is important in some regimes and unimportant in others.

The effect of each parameter's uncertainty was studied by:

- Associating probability distributions with the model parameters
- Computing probability distributions of the performance variables by using the system model
- Perturbating the distributions and observing the effect on the performance distributions

We computed the probability distributions by:

- Dividing the input and output variable spaces into finite intervals
- Computing the output values for every combination of input values (each variable interval is given a representative value)
- Summing the probabilities of input variable combinations to the appropriate output variable interval

In reviewing the study conclusions, one must keep in mind the limitations of this study, including the use of simple models and generic data.

1.4 SYSTEM MODELS

The system model used in this study is composed of three independent subsystems:

- The waste form and package
- The repository and nearby site
- The regional aquifer

These subsystems are pictured in Fig. 1-1. They are decoupled (independent) by assumption and the choice of variables.

The studies in Sections 5 and 6 consider nuclide transport through a system of serially connected flow path segments. Section 7 considers water flow through parallel paths.

To avoid the assumptions involved in modeling a water use system we chose to base our performance measure on activity. We used the peak (maximum over time) rate of activity release measured in curies per year (Ci/yr). We computed this peak rate of activity released for each of three groups of nuclides:

Group 1	^{99}Tc and ^{129}I
Group 2	Other fission products
Group 3	Actinides

The grouping is based on assumed similarity in retardation factors and dissolution (leach) rates. The disadvantages of using activity rather than dose as a basis for a performance measure are that the effect of the groups cannot be readily combined and that the output cannot be directly compared to other radiation standards.

Both spent fuel and high-level waste were considered as waste forms. The nuclide inventories were calculated using typical reactor parameters (Alexander et al., 1977).* Since the output scales with the amount of inventory, we arbitrarily chose an inventory resulting from the generation of 10^6 megawatt years of electricity (MWe·yr). This would be a typical

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*Alexander, C. W., et al., 1977, "Projections for Spent Fuel to be Discharged by the U.S. Nuclear Power Industry," Oak Ridge National Laboratory, ORNL TM-6008.

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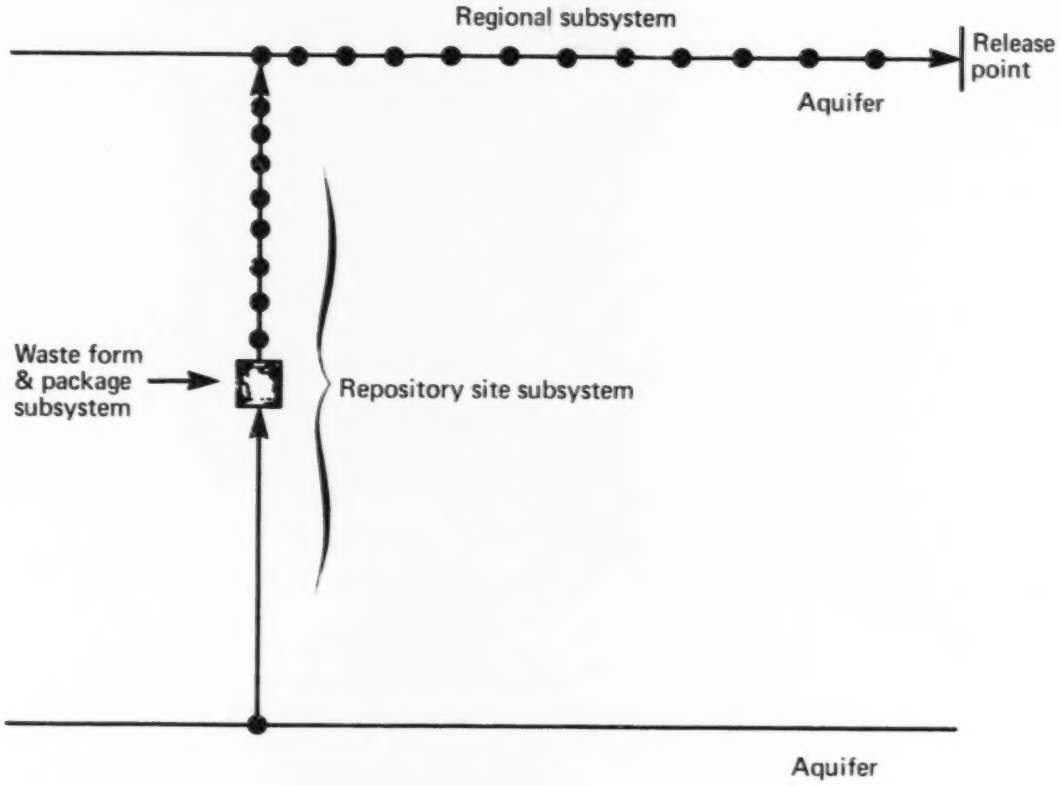

FIG. 1-1. Waste isolation subsystems.

inventory for a medium-size repository. The release from the waste form and package is assumed to be at a constant rate and is governed by two parameters, the release initiation time (t_0) and the release duration (t_D) (dissolution or leach time). Included in t_0 are the age of the waste at emplacement, the repository resaturation and repressurization time, and the canister life (corrosion) time. These terms, t_0 and t_D, could be a function of thermal effects, water chemistry, etc. These effects were not explicitly considered in this study. The entire inventory is represented as a point source. Refinement or more detail could be added to this model.

The water flow through the repository site or regional pathways is governed by D'Arcy's Law. The input parameters are head difference and length or head gradient, and hydraulic conductivity. The output is the D'Arcy velocity. The pore water velocity is then obtained by dividing by effective porosity. The transport of nuclides is assumed to be governed by the advection-dispersion (diffusion) equation. We assume one-dimensional pathways with longitudinal dispersion. The same retardation factor is assumed for all nuclides in the same decay chain. The transport equation is solved using Green's functions with semi-infinite boundary conditions. The input parameters are water velocity, retardation factor, dispersion constant, and path length. The output is the transit time and the spread. For serially connected pathways (repository site and regional aquifer) the total transit time is the sum of the transit times, and the square of the waste-pulse spread is the sum of the squares of the pulse spreads. To compute the flux of waste released we integrate over the path response and dissolution functions. The activity released is obtained by multiplying the flux by the activity function which depends on time. For our performance measure we took the maximum (over time) of this product.

1.5 PARAMETRIC ANALYSIS

The purpose of the analysis was to determine the areas of dominance for a few high-level parameters. We chose parameters primarily characteristic of the waste form and package (dissolution time) and the transport of nuclides through the site and region (transit time). This analysis is not limited to a specific example or scenario (as in Section 6) and could be used as a preliminary analysis for many different isolation systems. This general, high-level look provides basic understanding of the model behavior used to

interpret the analysis in Section 6 (see especially Section 6.8). The parameters and their ranges are listed in Table 1-1. The deterministic results of the analysis are presented in the form of contour plots as in Figs. 1-2 and 1-3. From Fig. 1-2, which is for actinides from spent fuel with little dispersion, we see that the peak activity released depends only on the transit time when the transit time is larger than the dissolution time. By comparing Figs. 1-2 and 1-3 we see that the actinide activity released is about an order of magnitude greater for spent fuel than for high-level waste. This is, of course, an obvious result since the high-level waste has most of the U and Pu removed. To put these results in perspective, a 100 Ci/yr release into a river flowing 10^{18} cm^3/yr (typical of the Colorado River) gives a concentration of 10^{-16} Ci/cm^3, which is three or four orders of magnitude less than the natural activity of the earth's surface.*

Some general conclusions can be drawn from the Parametric Analysis Results:

- Performance (peak activity release rate) is usually more sensitive to the larger of the transit time or dissolution time.
- Actinide release rate is greater for spent-fuel than for high-level waste.
- Dispersivity does not significantly influence performance.

A probabilistic parametric analysis was performed (Section 5.3) for the same parameters. An uncertainty of two orders of magnitude was assumed for

TABLE 1-1. Parameters and ranges for parametric analysis.

Transit time (T)	10^3 - 10^6 yr
Dissolution time (T_D)	10^3 - 10^6 yr
Release initiation time (T_D)	500 yr
Transit time/spread (T/S)	1, 10
Inventory type	Spent-Fuel (SF), High Level Waste (HLW)
Inventory amount	10^6 MWe·yr
Nuclide groups	I, Tc; other fission products; actinides

*M. Eisenbad, Environmental Radioactivity (Academic Press, New York, 1973), Chapter 7.

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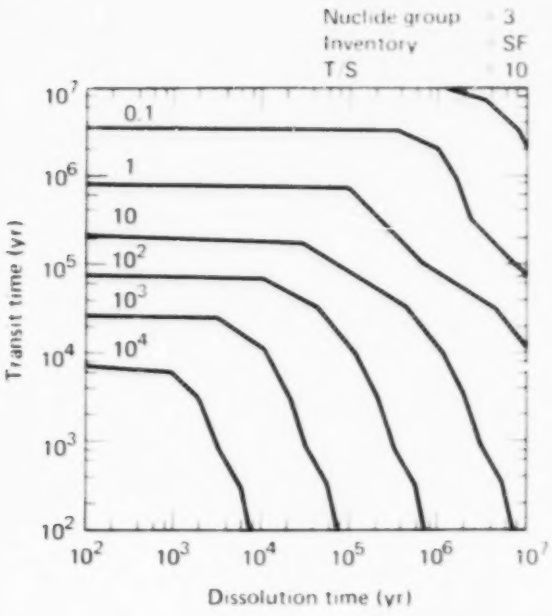

FIG. 1-2. Peak activity release rate (Ci/yr) for actinides from 10^6 MWe·yr of spent fuel as a function of dissolution and transit times.

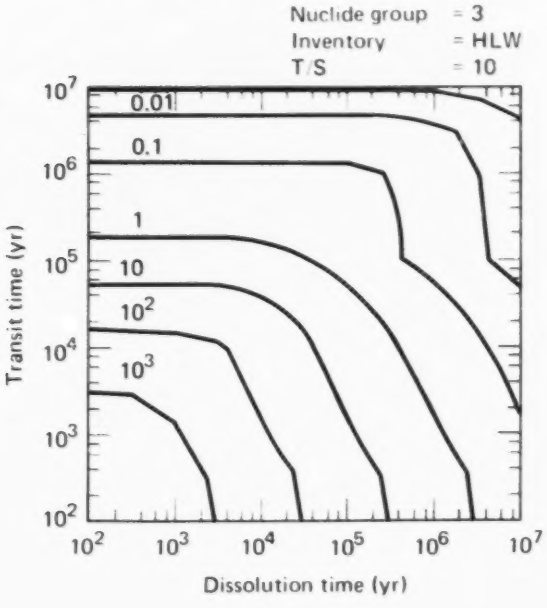

FIG. 1-3. Peak activity release rate (Ci/yr) for actinides from 10^6 MWe·yr of high-level waste as a function of dissolution and transit times.

the transit and dissolution time. The results confirmed the conclusions drawn from the deterministic analysis.

1.6 ANALYSIS OF A WASTE ISOLATION SYSTEM IN BEDDED SALT

We conducted a probabilistic analysis of a hypothetical repository for spent fuel in bedded salt (Section 6). The analysis assumed scenarios where the repository was substantially degraded below the nominal performance of a bedded salt repository. The system analyzed is shown in Fig. 1-1. The failure scenario assumes a flow path connecting the repository to an underlying aquifer and a fracture zone (associated with a sealed shaft and tunnel) connecting the repository to an overlying aquifer. The values of the parameters characterizing these pathways and the waste form/package are given in Table 1-2.

The purpose of the analysis is to determine how much each subsystem contributes to the system performance, and which parameters dominate the performance uncertainty. Given the flaws that allow substantial water flow through the repository, we computed probability distributions of the peak-release rates of activity for each nuclide group. In general, the uncertainty range (1st to 99th percentiles) of input parameters was an order of magnitude above and below the median values given in Table 1-2. The dominance of parameters was determined from uncertainty sensitivity analyses; that is, after the basic uncertainty calculation, the performance was recalculated setting the uncertain parameters to their median values one at a time.

The probability distributions of the outcomes (peak rate of activity release) are summarized using bar graphs (Fig. 1-4 is an example of a computed probability distribution). The horizontal bar below the curve corresponds to the vertical bars in Fig. 1-5. The percentile points are determined by adding the probabilities from the left. Figure 1-5 shows a bar graph for each of four cases. These cases are presented on the same graph for easy comparison. The horizontal ticks on each bar mark the 1st, 25th, 50th, 75th, and 99th percentile values of the computed distribution. The asterisk marks the mean value of the distribution.

An uncertainty sensitivity analysis was performed for each separate subsystem. This analysis identified the subsystem model parameters dominating the uncertainty about the performance of each subsystem.

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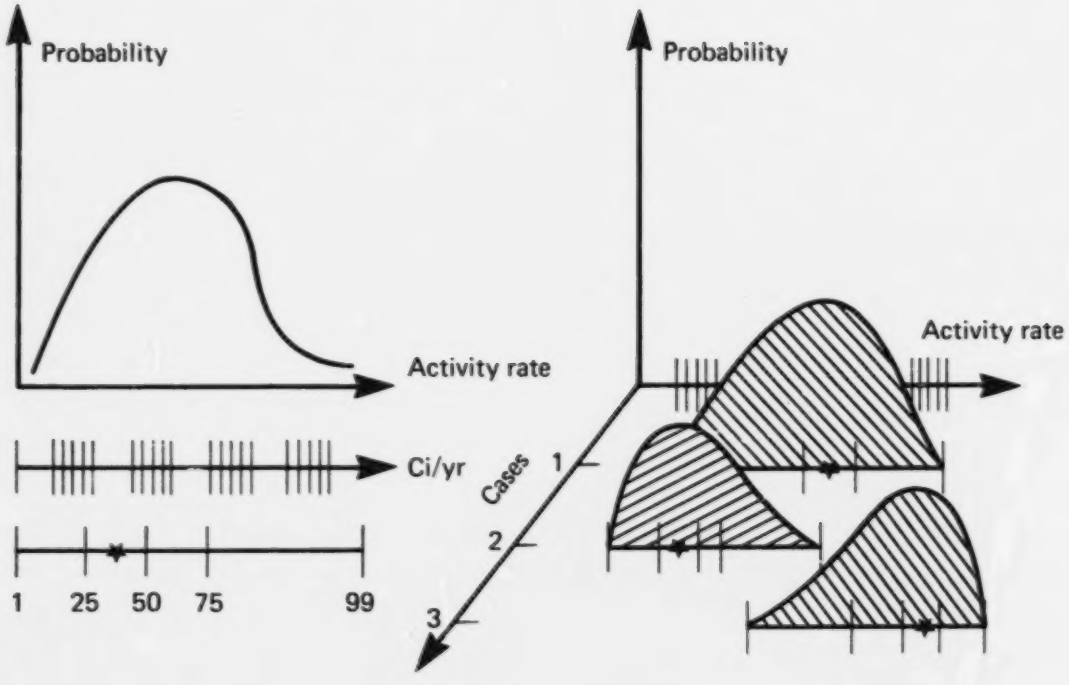

FIG. 1-4. Bar graph representation of a probability distribution.

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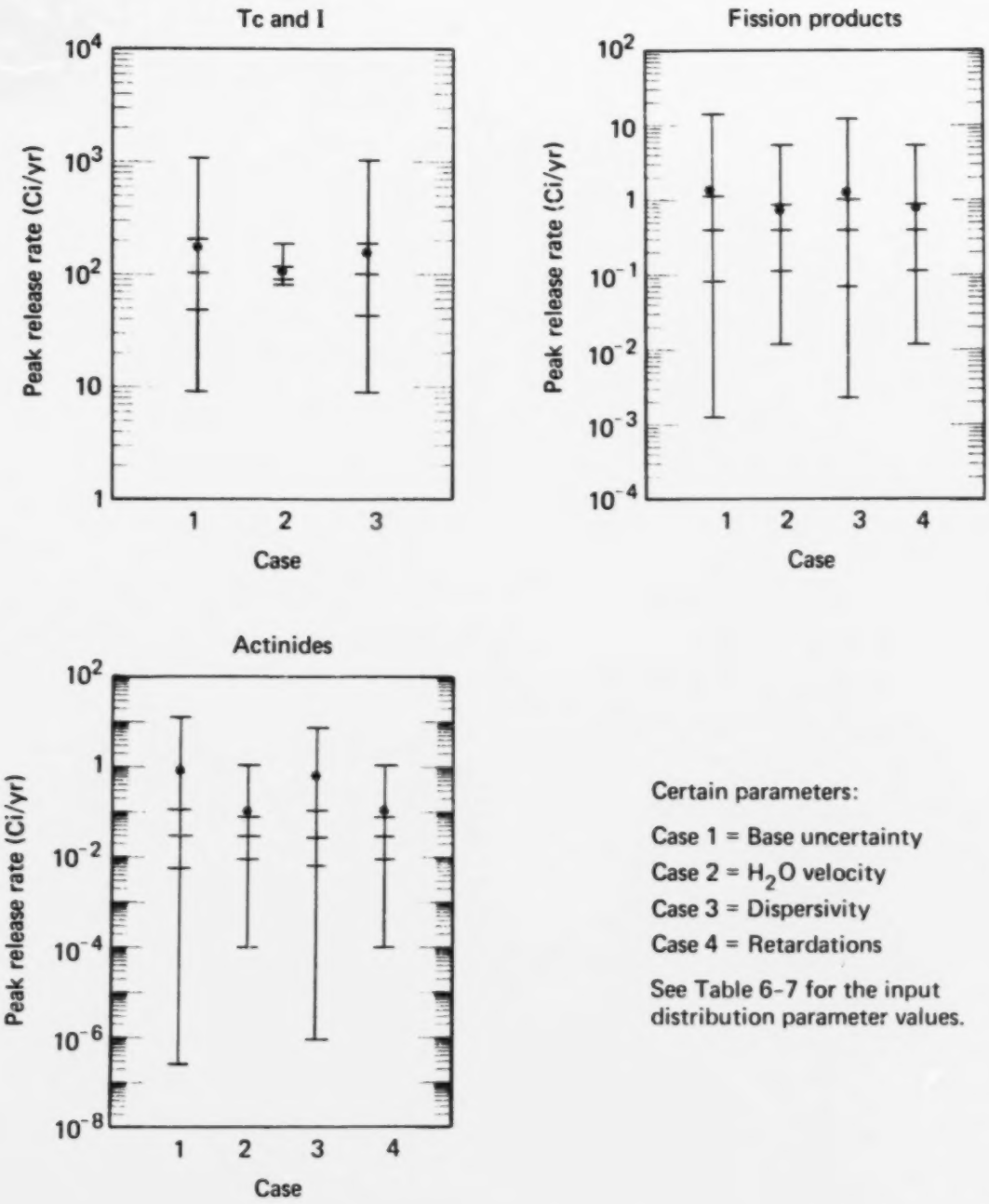

Certain parameters:

Case 1 = Base uncertainty

Case 2 = H_2O velocity

Case 3 = Dispersivity

Case 4 = Retardations

See Table 6-7 for the input distribution parameter values.

Horizontal bars represent the 1st, 25th, 50th, 75th and 99th percentiles.
*represents the mean value.

FIG. 1-5. Uncertainty sensitivity analysis of the aquifer (regional subsystem).

Figure 1-5 shows the performance of the aquifer assuming the whole inventory of 10^6 MWe·yr of spent fuel was instantaneously released at the input end of the aquifer 50 yr after being removed from reactors. The results show that an uncertainty in dispersivity of 400 m to 10 km has little effect on the performance of a 10-km aquifer.

TABLE 1-2. Subsystem parameters--median values.

Waste Form and Package	
Inventory type	Spent Fuel
Inventory amount	10^6 MWe·yr[a]
Release initiation time	500 yr
Dissolution time - Tc, I and fission products	5000 yr
Dissolution time, actinides	10^5 yr
Repository Site-Fracture Zone Below Repository	
Length	300 m[a]
Area	10^4 m^2
Hydraulic conductivity	0.1 m/yr
Repository Site-Fracture Zone Associated with Shaft and Tunnel	
Length	1200 m[a]
Area	100 m^2
Hydraulic conductivity	1 m/yr
Longitudinal dispersivity	50 m
Effective porosity	0.001
Retardation factor for Tc, I and fission products	10
Retardation factor for actinides	100
Regional Aquifer	
Length	10 km[a]
Water velocity	2 m/yr
Longitudinal dispersivity	2000 m
Retardation factor for Tc, I and fission products	100
Retardation factor for actinides	1000
Head difference between upper and lower aquifers	10 m[a]

[a]Indicates no uncertainty.

A similar analysis was conducted for the repository site subsystem. From results appearing in Section 6* we can see that the uncertainty in the hydraulic conductivity, porosity, and retardations of the flawed shaft dominated the uncertainty in the performance of the subsystem. Of course, this result depends on the relative values of the upper path and lower path parameter distributions chosen for this scenario.

The analysis of the waste form/package subsystem assumes no transit time. Waste is released at a constant rate beginning at t_0 and continuing for a duration t_D. Although the purpose of this assumption is to analyze this subsystem alone, we could think of this as a limiting case resulting from an extreme well intrusion scenario. From results presented in Section 6** we can see that the uncertainty in the peak-release rate of the fission products was sensitive to the uncertainty in the time-of-release initiation (t_0). The uncertainties in the technetium, iodine, and actinide outcomes were more sensitive to the uncertainty in the dissolution times (t_D).

The performances of the subsystems are compared in Fig. 1-6. The aquifer, case 3, is the same as the case 1 in Fig. 1-5. By comparing cases 1, 2, and 3 with case 4, the combined system, in Fig. 1-6, we see that for the fission products and actinides the regional aquifer is the dominant subsystem. The waste form and package subsystem is the most effective subsystem in reducing the peak-release rate of technetium and iodine. It is not surprising that the vertical path fails to dominate the performance of the system for any radionuclide group, since we assumed that the integrity of the host media is compromised by fractures. Any combination of one, two, or all three technetium and iodine subsystems (except the vertical path alone) produces distributions with percentiles and mean values within an order-of-magnitude range. For fission products and the actinides, any combination of two subsystems, or the aquifer alone, produces distributions with the 50th, 75th and 99th percentiles within an order-of-magnitude range.

Figure 1-7 gives the results of an uncertainty sensitivity analysis for the complete system. The sensitive parameters from each subsystem were included in the analysis. If a subsystem's performance was insensitive to a parameter's uncertainty, that parameter was set certain at its median value in

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*See Fig. 6-6.

**See Fig. 6-5.

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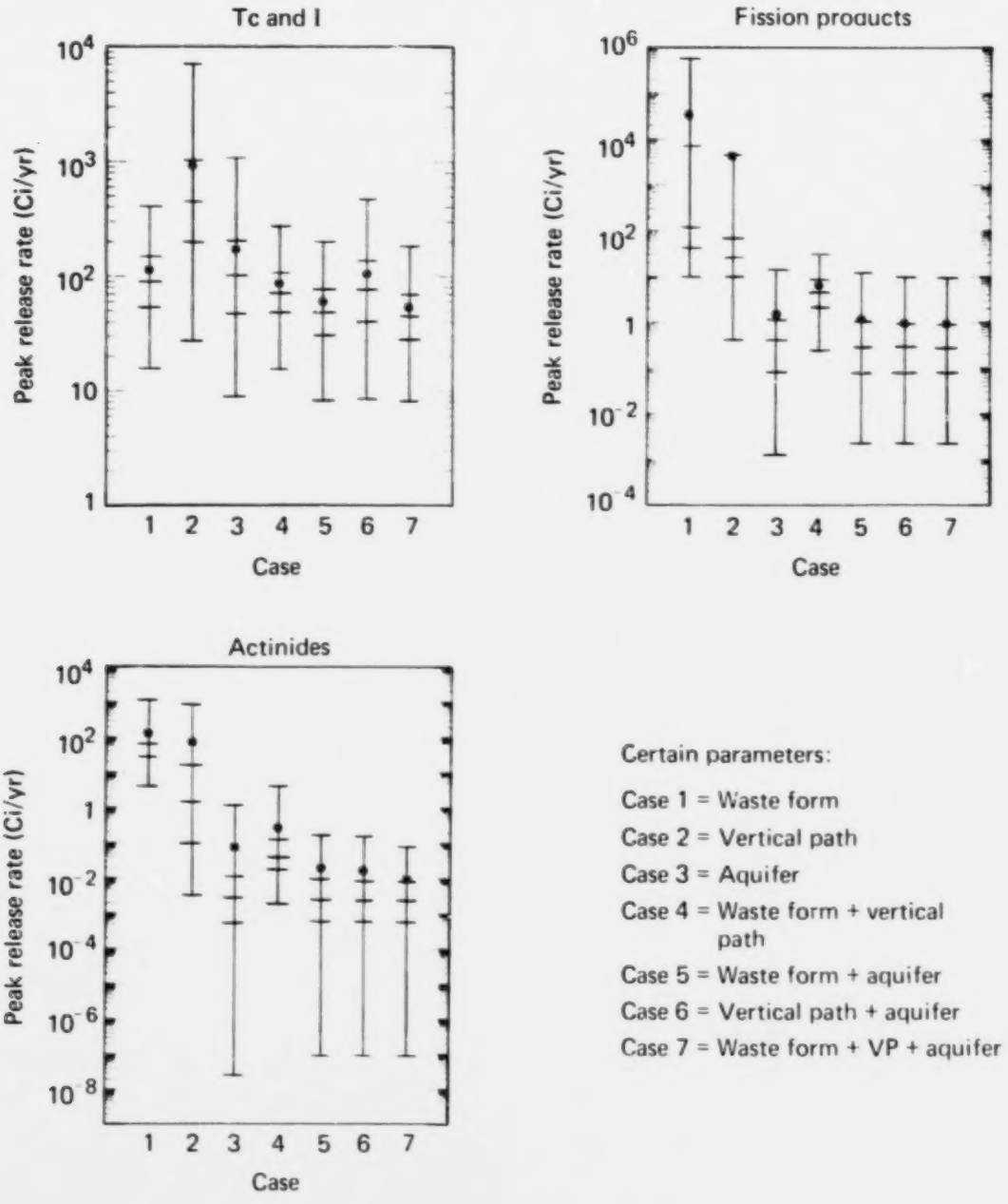
Tc and I
Fission products
Actinides
Peak release rate (Ci/yr)
Case
1 2 3 4 5 6 7
Certain parameters:
Case 1 = Waste form
Case 2 = Vertical path
Case 3 = Aquifer
Case 4 = Waste form + vertical path
Case 5 = Waste form + aquifer
Case 6 = Vertical path + aquifer
Case 7 = Waste form + VP + aquifer

Horizontal bars represent 1st, 25th, 50th, 75th and 99th percentiles.
*represents the mean value.

FIG. 1-6. Comparison of probability distributions for peak release rates of separate subsystems and aggregated subsystems.

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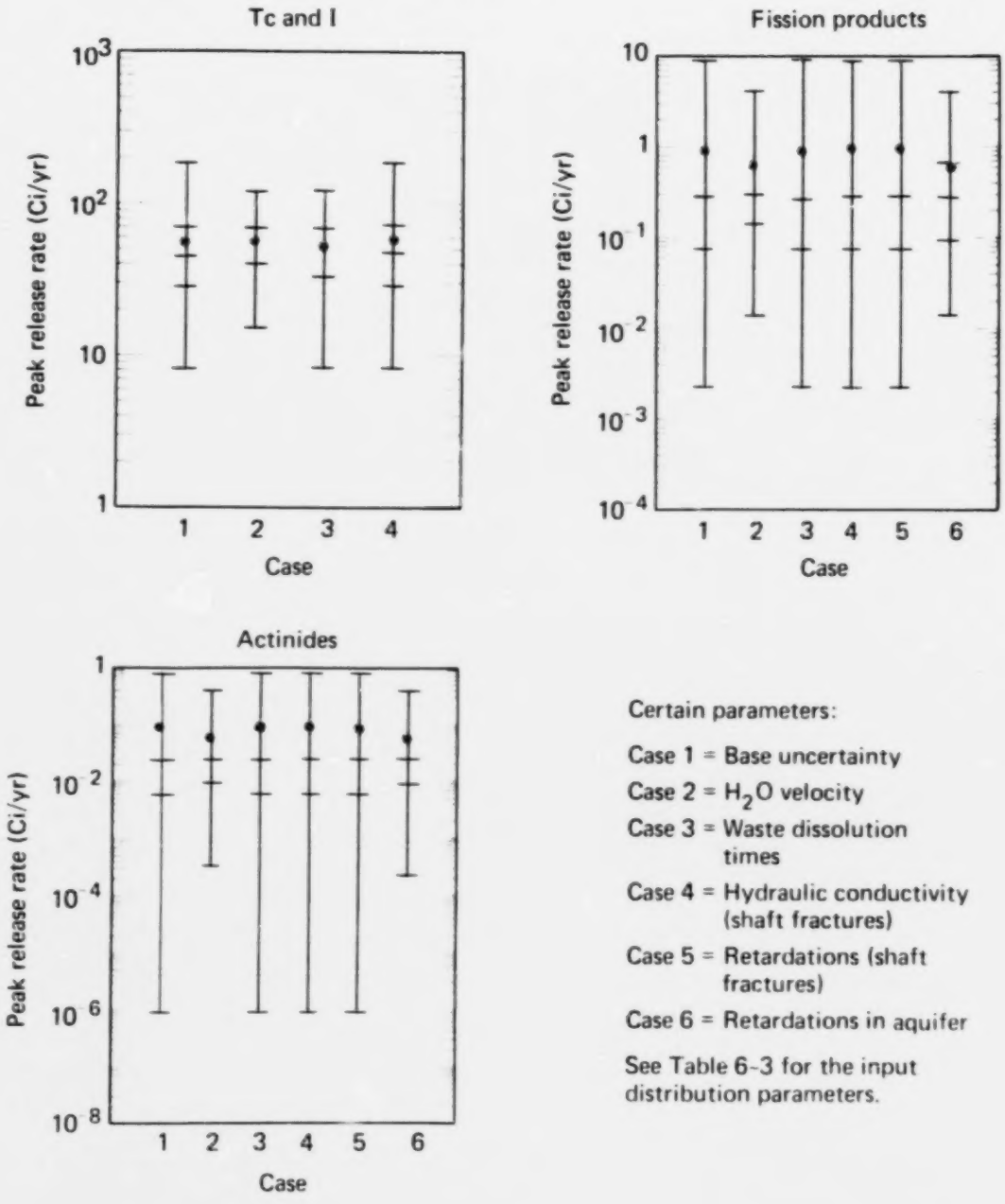

Horizontal bars represent the 1st, 25th, 50th, 75th and 90th percentiles.
*represents the mean value.

FIG. 1-7. Uncertainty sensitivity analysis of complete system.

the analysis of the complete system. To summarize the results, the parameters with greatest effect on the probability distributions of peak release rates were:

- Water velocity in the aquifer (Groups 1, 2, 3)
- Waste form dissolution time (Group 1)
- Waste particle retardations in the aquifer (Groups 2, 3)

The group numbers in parentheses indicate the groups most affected by the parameter.

Uncertainties about parameters for the repository site have little effect on system uncertainty, since system performance is dominated by the waste form subsystem for Tc and I, and by the regional subsystem for the other fission products and actinides. Again, this may be expected since the probability distributions for the vertical path parameters were selected to represent compromised repository barrier layers.

From Figs. 1-6 and 1-7 we can confirm the intuitive conclusion that when there is a dominant subsystem the uncertainty in the performance of the overall system is most sensitive to the uncertainty in parameters of that subsystem. It is difficult and, therefore, inadvisable to come to specific conclusions as to which parameter uncertainties are most important, in general, based on analysis of a single scenario. This is particularly true when the probability of that scenario has not been considered. Thus, conclusions based on specific quantitative results apply only to this system and scenario. The most limiting aspect of the analysis is that we studied only one flow network. On the other hand, the uncertainty associated with the network parameters allows various interpretations of the nature of the flow path.

1.7 HYDROLOGY WITH BRANCHING

The studies reported in Section 6 dealt only with series flow paths. Since branching flow is potentially important for modeling multiple shafts or shafts and flows, we undertook a study of parallel pathways. The study was limited to analysis of the flow (hydrology). A more detailed model of a repository would be necessary to determine the splitting fractions for an analysis of the transport of waste.

A simple network, Fig. 1-8, was used to model the flow. We determined the dependencies of the flow rates in terms of the transmissivities and the head differences.

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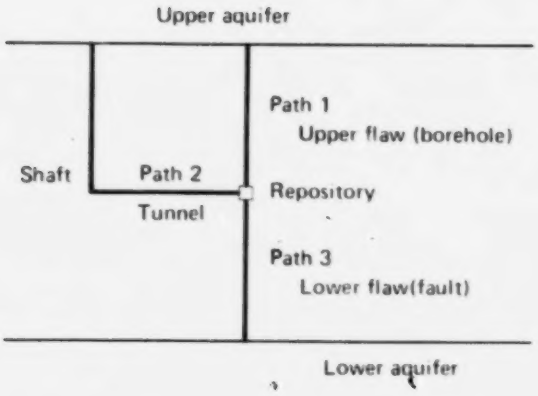

FIG. 1-8. Parallel path system.

Analytic results and contour plots are presented in Section 7. The numerical data allow us to confirm our intuition in many cases. In other cases nonintuitive results appear. For example, it is possible to have combinations of transmissivities and head drops where there is no flow in the upstream path. The conditions under which these combinations occur do not involve the transmissivity of the upstream path in question. If one of the flaws is a ventilation shaft, and the other is the main shaft, it might be possible to choose the relative positions of the two flowpaths so that the flow in the fast pathway would be zero. Careful consideration of such factors in repository design may significantly reduce the risk of waste migration.

1.8 CONCLUSIONS

Our work began by investigating the simple notion of ranking parameters, based on the effect changes in their values had on deterministic and probabilistic system performance. Over the range of possible parameter values, each parameter has regions of dominance and regions where the parameter has little effect. Our observations lead us to seriously doubt the value of any sensitivity analysis or response-surface technique based on small perturbations about a "base" point.

It is more useful to describe system performance in terms of a few high-level variables. The dependence of system performance on these variables can be ascertained from the plots presented in Section 5. Only in some limited regions is any kind of ranking meaningful.

In Section 6, instead of the higher-level variable, transit time, site and regional parameters are used. The results clearly illustrate how much each subsystem (waste form and package, repository site, and regional aquifer) contributes to the performance of the complete system. These specific results lead to some generalizations about the behavior of a waste isolation system; and illustrate the value of conducting such analysis for real sites and designs.

In the example systems analysis of a flawed repository, the waste form/package dominated the performance of the system in controlling Tc and I, and the regional aquifer dominated control of the other fusion products and actinides.

To realize a substantial improvement in overall system performance, we must improve a weaker subsystem to approximately the level of the dominant

subsystem. For example, increasing the value of the waste dissolution time had very little effect on the system's performance until the median time of the probability distribution was increased by three orders of magnitude (See Fig. 6-16).

There are cases where there are no dominant subsystems. If the transit or dissolution time is such that the activity is changing rapidly,* the performance of combined subsystems can be substantially better than that of the individual subsystems.

1.9 ADDITIONAL WORK

A perspective of how uncertainty analysis "fits in" can be obtained from Fig. 1-9. Our work has focused on those areas represented by boxes with shaded corners. Additional work in the following areas is suggested:

- Site specific analysis
- Development and evaluation of uncertainty analysis methods
- Detailed analysis of subsystems
- Validation of models

1.9.1 Site Specific Analysis

The methodology presented in this report was applied only to hypothetical systems and used generic data. This application is useful as a first step; however, the critical test of any method must be its usefulness in the real world. A site (and design) specific analysis could guide more detailed analysis necessary for a comprehensive performance assessment.

A necessary step in this analysis is the involvement of people intimately familiar with the site. Only with their help can consistent data and applicable models be developed for the analysis. This work would include the identification of failure scenarios and their relative likelihoods.

1.9.2 Development and Evaluation of Uncertainty Analysis Methods

In our analysis the probability distributions for model parameters were assumed to be independent. Decoupling systems can, in some cases, ignore

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*See Figs. 5-15 through 5-19 in Section 5.

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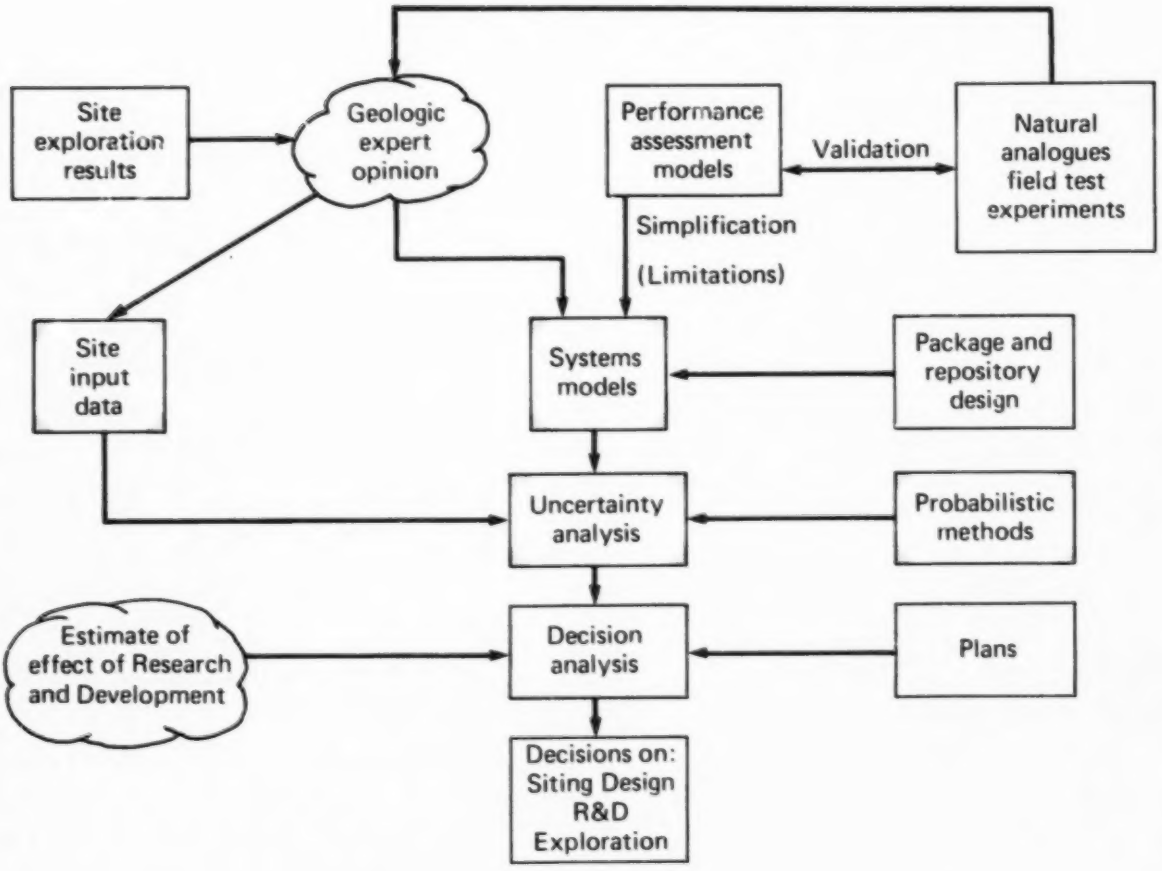

FIG. 1-9. Information flow through uncertainty analysis.

important effects. For example, waste dissolution rates may depend on the water-flow rate through the repository. Some correlations between subsystems, and between parameters of the same subsystem, could be included in further studies.

To properly develop and to evaluate probabilistic methods a knowledge of their intended use is necessary. Therefore, this effort should identify some of the decisions to be made and the framework (criteria, alternatives, etc.) in which they are to be made. In particular, estimates of the likelihood of R&D outcomes should be included.

1.9.3 Detailed Analysis of Subsystems

Our analysis made use of simple models, since we were interested in the performance of the total system. If attention is focused on a subsystem, we can afford to use more detailed models; for example, a detailed model of the waste form/package system must be used to investigate the feasibility of a 1000-yr canister.

A point source repository might be adequate to calculate performance at great distances; however, to calculate the hazard of a well-intrusion scenario a more detailed repository model is necessary. Repository-scale hydrology models have not received much attention and could be important in design decisions.

With the use of a water use model, our calculations could yield dose as a performance measure. With some development we could relax the nuclide group assumption and concentrate on selected nuclide chains.

1.9.4 Validation of Models

To place confidence limits on our results, an extensive effort involving more detailed models, experiments, and field tests should be undertaken. The first step in this direction should be to establish the quantitative effects of the simplifying assumptions made in going from detailed models to systems level models. In particular, the conditions under which, and the degree to which, the one-dimensional and isothermal assumptions are valid should be established.

APPENDIX A

This appendix contains the figures from Sections 5 and 6 referred to in Section 1. (These figures are in the order referenced in Section 1.)

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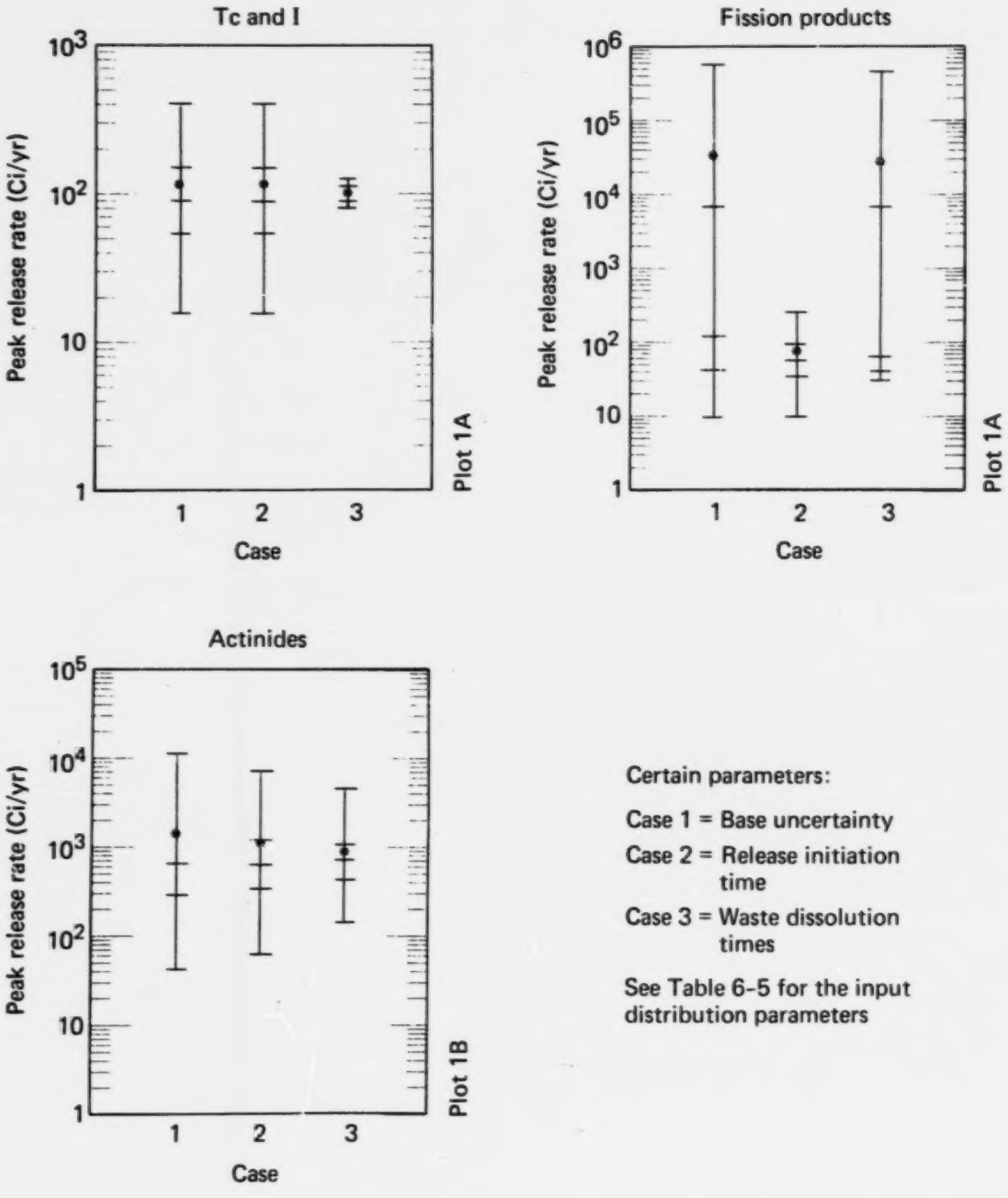

Horizontal bars represent the 1st, 25th, 50th, 75th and 99th percentiles.
*represents the mean value.

FIG. 6-5. Uncertainty sensitivity analysis of the waste form system.

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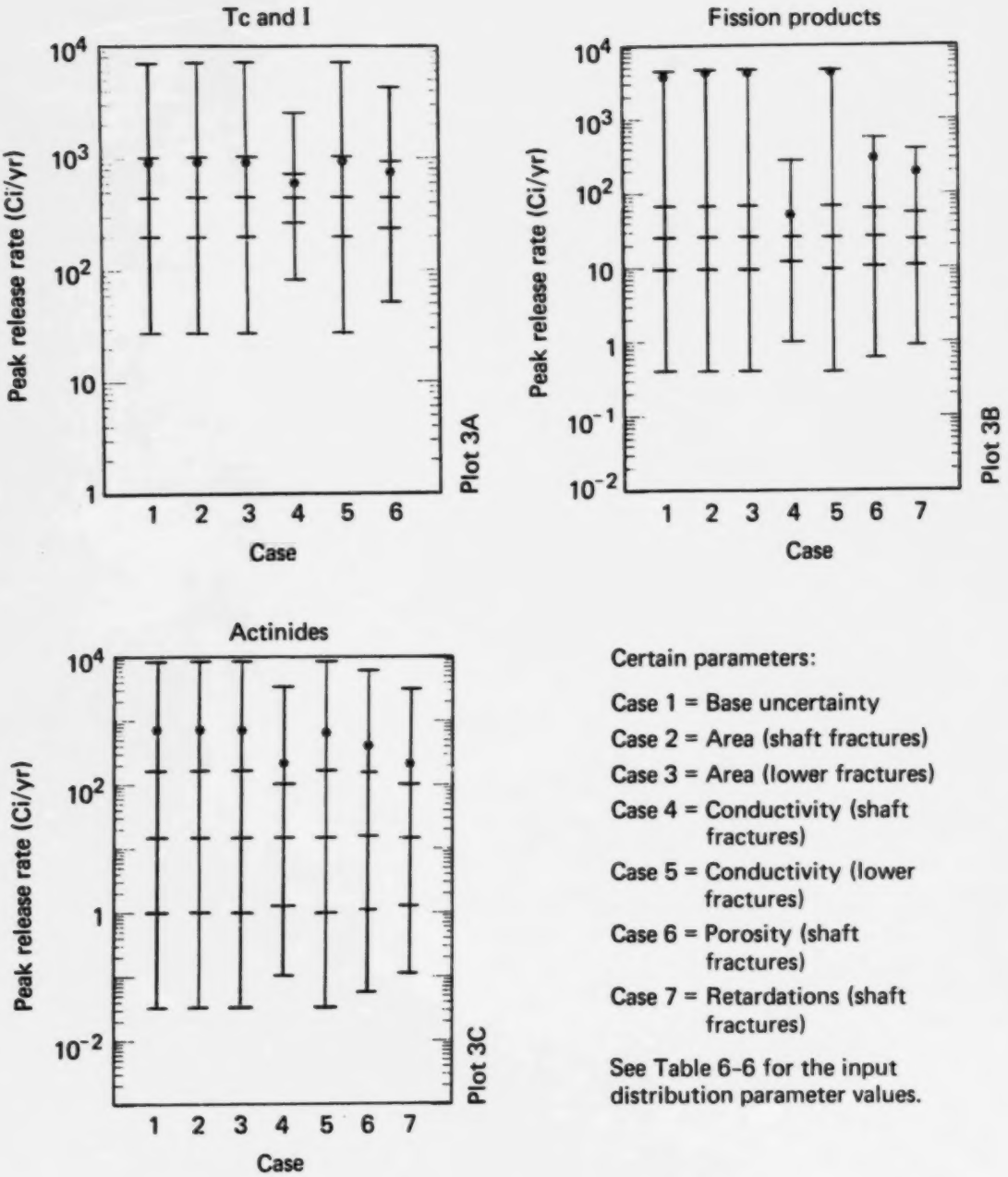

FIG. 6-6. Uncertainty sensitivity analysis of the vertical path through the repository (repository site subsystem).

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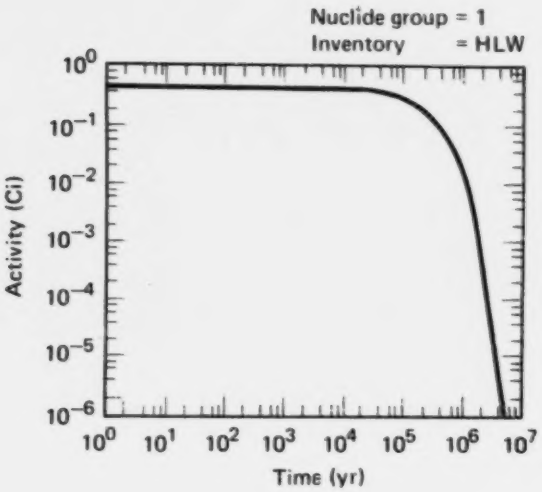

FIG. 5-15. Activity per MWe·yr vs time (Nuclide Group 1, HLW inventory).

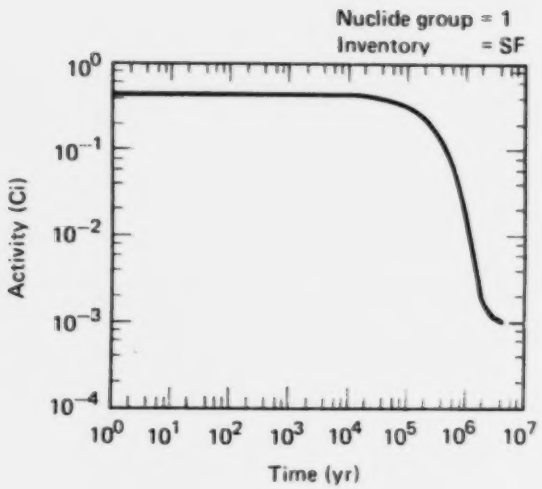

FIG. 5-16. Activity per MWe·yr vs time (Nuclide Group 1, SF inventory).

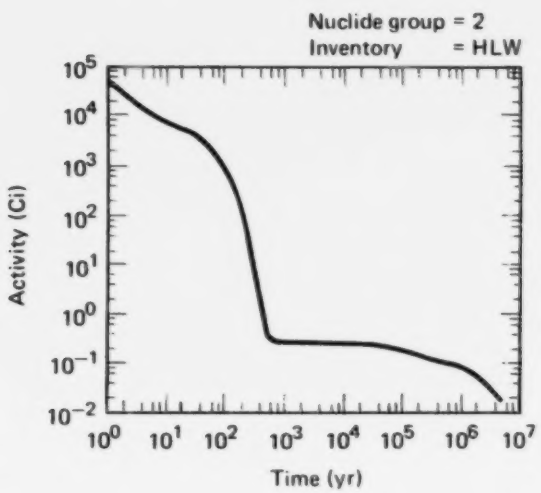

FIG. 5-17. Activity per MWe·yr vs time (Nuclide Group 2, HLW inventory).

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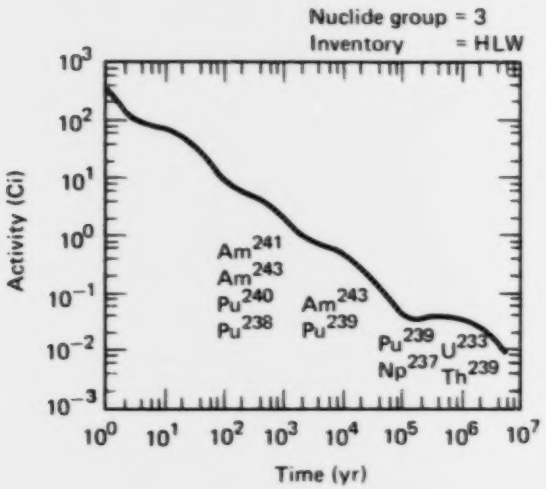

FIG. 5-18. Activity per MWe·yr vs time (Nuclide Group 3, HLW inventory).

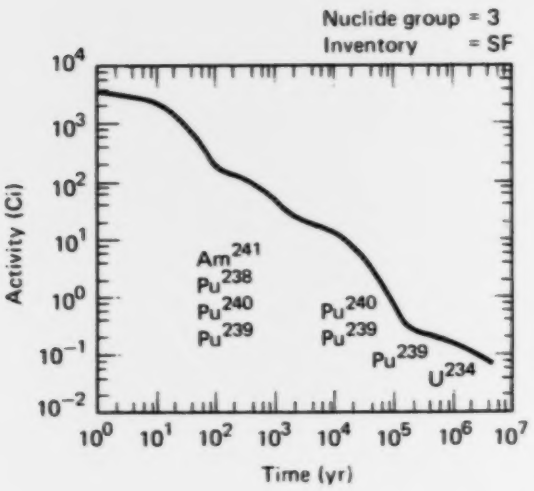

FIG. 5-19. Activity per MWe·yr vs time (Nuclide Group 3, SF inventory).

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APPENDIX B

This appendix is a reproduction of the Table of Contents for ONWI-352 (UCRL-53142).

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